



Practical Software Diversification for WebAssembly

JAVIER CABRERA-ARTEAGA

Doctoral Thesis in Computer Science
Supervised by
Benoit Baudry and Martin Monperrus
Stockholm, Sweden, 2023

TRITA-EECS-AVL-2020:4
ISBN 100-

KTH Royal Institute of Technology
School of Electrical Engineering and Computer Science
Division of Software and Computer Systems
SE-10044 Stockholm
Sweden

Akademisk avhandling som med tillstånd av Kungl Tekniska högskolan framlägges
till offentlig granskning för avläggande av Teknologie doktorexamen i elektroteknik
i .

© Javier Cabrera-Arteaga , date

Tryck: Universitetsservice US AB

Abstract

Keywords: Lorem, Ipsum, Dolor, Sit, Amet

Sammanfattning

LIST OF PAPERS

1. ***WebAssembly Diversification for Malware Evasion***
Javier Cabrera-Arteaga, Tim Toady, Martin Monperrus, Benoit Baudry
Computers & Security, Volume 131, 2023, 17 pages
<https://www.sciencedirect.com/science/article/pii/S0167404823002067>
2. ***Wasm-mutate: Fast and Effective Binary Diversification for WebAssembly***
Javier Cabrera-Arteaga, Nicholas Fitzgerald, Martin Monperrus, Benoit Baudry
Under review, 17 pages
<https://arxiv.org/pdf/2309.07638.pdf>
3. ***Multi-Variant Execution at the Edge***
Javier Cabrera-Arteaga, Pierre Laperdrix, Martin Monperrus, Benoit Baudry
Moving Target Defense (MTD 2022), 12 pages
<https://dl.acm.org/doi/abs/10.1145/3560828.3564007>
4. ***CROW: Code Diversification for WebAssembly***
Javier Cabrera-Arteaga, Orestis Floros, Oscar Vera-Pérez, Benoit Baudry, Martin Monperrus
Measurements, Attacks, and Defenses for the Web (MADWeb 2021), 12 pages
<https://doi.org/10.14722/madweb.2021.23004>
5. ***Superoptimization of WebAssembly Bytecode***
Javier Cabrera-Arteaga, Shrinish Donde, Jian Gu, Orestis Floros, Lucas Satabin, Benoit Baudry, Martin Monperrus
Conference Companion of the 4th International Conference on Art, Science, and Engineering of Programming (Programming 2021), MoreVMs, 4 pages
<https://doi.org/10.1145/3397537.3397567>
6. ***Scalable Comparison of JavaScript V8 Bytecode Traces***
Javier Cabrera-Arteaga, Martin Monperrus, Benoit Baudry
11th ACM SIGPLAN International Workshop on Virtual Machines and Intermediate Languages (SPLASH 2019), 10 pages
<https://doi.org/10.1145/3358504.3361228>

ACKNOWLEDGEMENT

Contents

List of Papers	iii
Acknowledgement	v
Contents	1
I Thesis	3
1 Introduction	5
1.1 Background	5
1.2 Problem statement	5
1.3 Automatic Software diversification requirements	5
1.4 List of contributions	5
1.5 Summary of research papers	6
1.6 Thesis outline	6
2 Background and state of the art	7
2.1 WebAssembly	7
2.1.1 From source code to WebAssembly	8
2.1.2 WebAssembly’s binary format	9
2.1.3 WebAssembly’s runtime structure	11
2.1.4 WebAssembly’s control flow	13
2.1.5 WebAssembly’s ecosystem	14
2.1.6 WebAssembly’s binary analysis	15
2.1.7 WebAssembly’s security	16
2.2 Software diversification	17
2.2.1 Generating Software Diversification	17
2.2.2 Variants generation	17
2.2.3 Variants equivalence	17
2.2.4 Defensive Diversification	17

2.2.5	Offensive Diversification	17
3	Automatic Software Diversification for WebAssembly	19
3.1	CROW: Code Randomization of WebAssembly	20
3.1.1	Enumerative synthesis	21
3.1.2	Constant inferring	22
3.1.3	CROW instantiation	23
3.2	MEWE: Multi-variant Execution for WebAssembly	25
3.2.1	Multivariant generation	26
3.3	WASM-MUTATE: Fast and Effective Binary for WebAssembly	29
3.3.1	WebAssembly Rewriting Rules	30
3.3.2	E-Graphs traversals	31
3.3.3	WASM-MUTATE instantiation	32
3.4	Comparing CROW, MEWE, and WASM-MUTATE	34
3.4.1	Security applications	37
3.5	Conclusions	38
4	Exploiting Software Diversification for WebAssembly	39
4.1	Offensive Diversification: Malware evasion	39
4.1.1	Threat model and objective	40
4.1.2	Approach	40
4.1.3	Results	41
4.2	Defensive Diversification: Speculative Side-channel protection	42
4.2.1	Threat model	42
4.2.2	Approach	43
4.2.3	Results	43
4.2.4	Partial input/output validation	43
4.2.5	Some other works to be cited along with the paper. Mostly in the Intro	43
4.3	Conclusions	44
5	Conclusions and Future Work	45
5.1	Summary of technical contributions	45
5.2	Summary of empirical findings	45
5.3	Future Work	45
II	Included papers	47
	Superoptimization of WebAssembly Bytecode	51

CONTENTS	3
-----------------	----------

CROW: Code Diversification for WebAssembly	53
Multi-Variant Execution at the Edge	55
WebAssembly Diversification for Malware Evasion	57
Wasm-mutate: Fast and Effective Binary Diversification for WebAssembly	59
Scalable Comparison of JavaScript V8 Bytecode Traces	61

Part I

Thesis

